Geospatial and techno-economic analysis of wind and solar resources in India

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Abstract

Using geospatial and economic analysis, we identify abundant renewable resources in India — 850-3,400 GW for onshore wind, 1,300-5,200 GW for utility-scale solar photovoltaic (PV), 160-620 GW for concentrated solar power (CSP, with 6h-storage). However, these resources are concentrated in the western and southern regions. Deriving capital costs from India's 2017-18 auction prices, we estimate the 5th and 95th percentiles of levelized costs of energy generation ranging from USD 47-52 per MWh for solar PV and USD 42-62 per MWh for wind. Karnataka, Maharashtra, Tamil Nadu, and Telangana are the best states for access to high-voltage substations, but transmission investments in Gujarat, Rajasthan, Andhra Pradesh, and Madhya Pradesh are needed to harness significant renewable resources. More than 80% of wind resources lie on agricultural lands where dual land use strategies could encourage wind development and avoid loss of agriculturally productive land. Approximately 90% of CSP resources and 80% of solar PV resources are in areas experiencing high water stress, which can severely restrict deployment unless water requirements are minimized. Finally, we find co-location potential of at least 110 GW of wind and 360 GW of solar PV, which together could meet 35% of electricity demand in 2030.

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1. Introduction

India's greenhouse gas emissions rank third in the world [1]. More than 30% of these emissions are from coal-based electricity generation [1], which until recently, was the cheapest source of electricity. Technological advances and recent cost declines in solar photovoltaic (PV) and wind technologies have made these alternatives increasingly cost-competitive with coal generation [2, 3, 4]. If costs of wind and solar PV continue to fall, India could cost-effectively deploy and integrate very high renewable energy (RE) capacity, which could significantly reduce local and global environmental impacts of its electricity system. As of 2017, India had already installed 32.8 GW of wind (6.4% of the global wind capacity of 514 GW) and 19.3 GW of solar PV (5% of the global solar PV capacity of 391 GW) [5]. Further, the Government of India (GoI) has set ambitious targets for grid-connected RE—60,000 MW of wind and 100,000 MW of solar capacity by 2022 [6]. In addition, in its Nationally Determined Contribution (NDC), the GoI committed to a target of 40% of installed generation capacity from non-fossil fuel sources by 2030 [6].

Despite India's ambitious RE goals, there is little understanding of the siting barriers and opportunities in the scale up of wind and solar generation in India. Wind and solar resources depend on weather patterns and are often unevenly distributed across space. Therefore, quantifying regional potential is important for setting regional policies such as state-specific RE targets. Identifying suitable areas for RE deployment is also critical for land-use and transmission planning. If wind and solar technologies are to each supply half of India's electricity demand in 2030, direct land requirements for wind and solar plants could be as large as 25% and 10% of India's present urban area, respectively [7, 8].[2] Land acquisition in India has been a challenge, and land conflicts due to large infrastructure projects are common [9, 10].[3] Identify-

[2]Assumptions of land use factors are 9 MW/km^2 for wind and 30 MW/km^2 for both solar PV plants. Actual direct land-use requirements of wind plants, which mainly includes roads, turbine footprint, and transformer, is significantly smaller than the entire area occupied by a wind plant. Total and urban area estimates for India are from the World Bank.

[3]In a study analyzing 289 land-related conflicts in 2016, 15% of the total conflicts were

ing areas with high quality RE resources but with limited competing values such as agriculture or biodiversity can limit potential conflicts and accelerate deployment. Further, identifying best quality resources relative to existing grid infrastructure can enable prioritizing potential RE projects based on existing transmission infrastructure and early planning of high-voltage high-capacity transmission lines, which typically take longer to construct than RE plants [11]. Pursuing opportunities to co-locate wind and solar PV plants can reduce the overall land requirements for RE deployments and capitalize on transmission line extensions. Vast areas in India are under water stress [12], and avoiding solar plant development in such areas would be critical to limit competition for scarce water resources.

For India, most studies estimating renewable resource potential have focused on wind energy [13, 14, 15, 16, 17, 18, 19], with few studies providing estimates of solar potential [20, 21]. However, none of the India-focused studies have quantified the technical potential of all three RE technologies—wind, solar PV, and CSP—using the same methodological framework and assumptions, which precludes a comparison of siting barriers between technologies. To our knowledge, no existing study has estimated potential costs of developing these resources.

In this study, we spatially identify and quantify the techno-economic potential for electricity generation from onshore wind, utility-scale solar PV, and concentrated solar power (CSP, with 6hr-storage) technologies in India using various siting assumptions and physical and environmental constraints. To enable strategic spatial planning, we identify land-use and water siting constraints and explore co-location opportunities for informed solar and wind power plant siting. Numerous studies have quantified RE resource potential using geographic information systems (GIS) [22, 23, 24, 25]. We also estimate the levelized cost of electricity (LCOE) generation, interconnection costs using the nearest transmission substation, and costs to connect each project to the road network. Further, we evaluate risks posed by competing land-uses and water scarcity to future RE development in the country. Finally, we quantify synergies between RE technologies in India, specifically potential for co-locating wind and solar plants to make better use of land and transmission resources.

found to be in the electricity sector [9].

2. Methods

We adapted and built upon the Multi-criteria Analysis for Planning Renewable Energy (MapRE) modeling framework, which was first developed for and applied to regions in Africa [26]. MapRE is a spatial energy systems modeling framework that integrates renewable resource assessment and estimation of multiple criteria for decision making analysis [26]. The three stages of the MapRE methodology are shown in the flowchart in Figure .

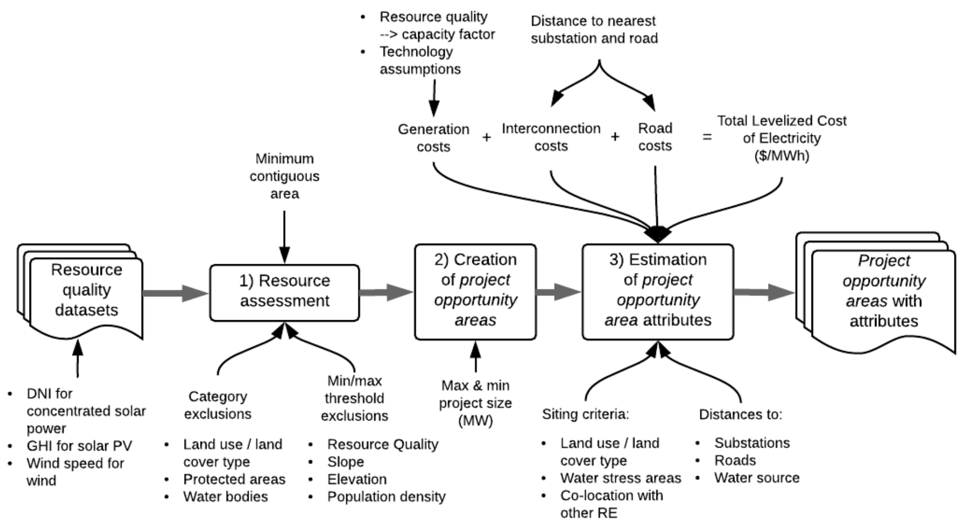


Figure 1: Methodology flow chart. Adapted from Wu et al. 26.

2.1. Renewable Energy Resource Assessment

We first identified areas that meet baseline technical, environmental, economic, and social suitability criteria for RE development. We relied on a combination of global and India-specific spatial and non-spatial datasets (Table A.7 in SI A). Using Python and the Arcpy package for spatial analysis, we estimated the resource potential by linearly combining exclusion criteria after applying industry-standard [22, 15, 14, 25, 27, 28] thresholds and buffers for the following data types: techno-economic (elevation, slope, renewable resource quality, water bodies), environmental (land-use and land-cover, protected areas), and socio-economic (population density) (Table 1 and Table A.7 in SI A). To identify economically-viable resources, we chose resource quality thresholds of 5.5 m/s wind speed or 200 W/m^2 power density for wind and 4.9 kWh/m^2/day or ~1800 kWh/m^2/y Global Horizontal Irradiance (GHI) for solar PV and Direct Normal Irradiance (DNI) for CSP.[4] We then imposed a minimum contiguous area of 2 km^2 for both wind and solar. The technology-specific land-use and land-cover (LULC) categories are listed in Table 1. We included agricultural land for wind because turbine footprints occupy only a small fraction of total plant area, leaving the rest for other uses. Although farmers could choose to install solar plants on agricultural areas for economic reasons, we chose to exclude those areas for solar to avoid conflict between energy and food. All analyses were performed at 500 m resolution using South Asia Albers Equal Area Conic projection.

We used empirical values of installed capacity per unit area (land use efficiency) of 9 MW/km^2 for wind, 30 MW/km^2 for solar PV, and 17 MW/km^2 for CSP with 6-hour storage to estimate the potential for installed generation capacity on the remaining areas deemed suitable for energy development [29, 26]. Unlike some studies, we did not exclude areas occupied by roads, railroads, and airports because of uncertainties in available data. To reflect uncertainties in land availability due to the presence of other infrastructure as well as ground realities such as land ownership and conflict areas, we applied a land use discount factor of 75% for both wind and solar technologies [28].

2.2. Project opportunity area attributes

Using a 5 x 5 km grid, we divided large contiguous suitable resource areas into representative utility-scale projects that we term "project opportunity areas" (POAs). These POAs range from 2 km^2 - 25 km^2 and have the potential to accommodate 4.5 - 56.25 MW size wind plants and 9 - 187.5 MW size solar power plants (assuming land use factors of 2.25 MW/km^2 for wind, 7.5 MW/km^2 for solar PV, and 4.25 MW/km^2 for CSP with 6-hour

[4]Wind speed threshold results in approximately a 20% capacity factor cut-off, similar to [22, 14, 15]. GHI threshold covers approximately all solar PV resources in India. DNI threshold is low relative to other studies [25, 21], but results in 18% capacity factor cut-off for CSP without storage.

Table 1: Included (In) categories from the National Remote Sensing Centre's land-use and land-cover data for all technologies.

Code	Class Name	Solar PV and CSP	Wind
1	Built-up (urban)		
2	Kharif (cropland: June-October)		**In**
3	Rabi (cropland: November-April)		**In**
4	Zaid (cropland: April-June)		**In**
5	Double/Triple (irrigated cropland)		**In**
6	Current fallow (cropland)		**In**
7	Plantation/orchard		
8	Evergreen forest		
9	Deciduous forest		
10	Scrub/degenerated forest		
11	Littoral swamp		
12	Grassland	**In**	**In**
13	Other wasteland	**In**	**In**
14	Gullied		
15	Scrubland	**In**	**In**
16	Water bodies		
17	Snow covered		
18	Shifting cultivation		**In**
19	Rann (Salt marsh in Kutch district, Gujarat state)	**In**	**In**

Kharif, Rabi, and Zaid are cropping seasons.

storage after applying a 75% land use discount factor). These sizes were selected to represent utility-scale wind and solar power plants.

For each POA, we estimated several technical and economic attributes (Table 2). We calculated average values for these attributes determined either by spatial overlap with other data (water stress areas, agricultural land, other RE resources for co-location opportunities) or distances from features such as substations, roads, and water bodies (see Figure 1). We used the resource quality to estimate capacity factors, which we then used along with two of the siting criteria—distances to transmission and road infrastructure—to estimate each POA's generation, transmission, and road components of the levelized cost of energy (LCOE) for each technology.

2.2.1. Capacity factor

Solar PV. Annual average capacity factor (CF) for each POA is the ratio of the estimated output of a power plant over a whole year to the potential

Table 2: Description of estimated project opportunity area (POA) attributes.

Attribute	Description
Area	Total area of the POA in units of square kilometers
Resource quality	Mean resource quality in terms of wind speed (m/s) or solar irradiance (kWh/m^2-day).
Capacity factor	Mean annual capacity factor of the POA for each technology estimated using average resource quality.
Electricity generation	Average annual electricity generation (MWh) estimated using each technologys capacity factor, land use factor, and land area.
Distance to nearest location	Straight-line distance from each POA to the nearest substation (with 1.3 terrain factor applied); road (with 1.3 terrain factor applied); and surface water body.
Generation LCOE	Average levelized cost of electricity (in INR/MWh or USD/MWh) for the generation component. Values were estimated using the location and technologys capacity factor and capital and operations and maintenance cost assumptions.
Transmission interconnection LCOE	Average levelized cost of electricity (in INR/MWh or USD/MWh) for the transmission component for each technology using distance to nearest substation and transmission infrastructure unit cost assumptions.
Road LCOE	Average levelized cost of electricity (in INR/MWh or USD/MWh) for the road component, using distance to nearest road, road infrastructure unit cost assumptions, and assuming 50 MW of installed capacity per POA.
Total LCOE	Average total levelized cost of electricity (in Rs/MWh or USD/MWh) estimated by summing the individual component LCOEs for generation, transmission infrastructure (nearest substation), and road.
Co-location potential	A binary score of 0 or 1, with 1 indicating that a POA is suitable for the development of another renewable energy technology. A score was determined for wind and solar PV technologies, which can be co-located.
Water stress score	A ”Baseline Water Stress Score” from the World Resources Institute’s Aquaduct Water Risk Atlas, which varies from 0 to 5, with 4-5 indicating ”Extreme Water Stress” and 3-4 indicating ”High Water Stress”.

output of that plant if it were to generate continuously at its rated capacity. In addition to the resource quality, CFs for solar PV depend on the type of system. Single and dual axis tracking systems will have higher CFs but also greater costs compared to fixed tilt systems. Although single-axis tracking systems dominated the U.S. utility-scale solar market in 2015 [30], the Indian market still preferred fixed tilt systems, likely due to reasons such as lower steel and labor costs (IHS, 2015). In this study, we assumed that all solar PV systems are south-facing fixed tilt systems, with their tilt equal to the latitude of the location. The CF depends on the solar irradiance on the tilted surface of PV panels, which in turn depends on the GHI and the latitude of the location. We had access to high spatial resolution (10 km) annual average GHI data across India but high temporal resolution (hourly) solar radiation data, essential to estimate irradiance on the tilted surface, for only a limited number of locations. To estimate the non-linear relationship between GHI and CF, we first manually chose 617 locations spatially well-dispersed across suitable solar resource areas to capture locations across India's widely varying latitudes. We then estimated annual average CFs for those locations using hourly solar radiation, temperature, and wind speed data from the National Solar Radiation Database (NSRDB) [31] in the System Advisor Model (SAM) [32] (see Table 3 for solar PV-specific assumptions).[5] We then spatially associated each POA to the nearest location with a simulated CF and resource quality and estimated each POAs CF by proportionally adjusting the closest simulated CF using the POA's average resource quality.

CSP. Other than the DNI, the CF for a CSP plant mainly depends on the type of technology (e.g. parabolic, solar power tower) and the amount of thermal storage. Thermal storage can enable CSP plants to provide a valuable service of shifting energy generation to times of high energy prices [38]. In this study, we assume a generic CSP plant with 6-hour storage.

Similar to solar PV, only annual average DNI data were available at a high spatial resolution across India. Unlike solar PV, CF of CSP plants, reflectors of which track the sun, are not significantly affected by latitude of the location. Therefore, a relatively small number of locations with detailed CF simulations were deemed sufficient to estimate the relationship between DNI and annual CF. Assuming a generic CSP plant with 6 hours of storage and a solar multiple of 2.1, we first simulated CFs for 19 locations across

[5]The solar radiation data in NSRDB were developed by the National Renewable Energy Laboratory (NREL) using the State University of New York (SUNY) semi-empirical model and the meteorological data are from the National Aeronautics and Space Administration (NASA)'s Modern-Era Retrospective Analysis for Research and Applications (MERRA).

Table 3: Parameters in capacity factor and levelized cost of electricity estimates

Parameters	Wind	Solar PV	CSP
Land use factor [MW/km^2]	2.25[a] – 9[b]	7.5[a] – 30[c]	4.25[a]–17[c,d]
Wind-specific			
Hub height	80 *meters*	-	-
Array and collection loss (η_a)	15%[e]	-	-
Outage rate (η_o)	2%[f]	-	-
Solar PV-specific			
DC-to-AC ratio	-	1.1	-
Tilt of fixed-tilt system	-	Latitude	-
Azimuth	-	180^o	-
Inverter efficiency losses	-	4%[f]	-
Wiring, soiling, availability losses	-	14%[e]	-
Ground cover ratio	-	0.4[f]	-
CSP-specific			
Solar multiple	-	-	2.1
Auxiliary consumption including losses	-	-	10%[f]
Outage rate	-	-	4%[f]
Storage duration	-	-	6 *hours*
Costs			
Generation capital [USD/kW] ($c_{g,t}$)	1,250[g]	850[g]	7500[h]
Generation fixed O&M [USD/kW] ($o_{f,g}$)	15[i]	10[i]	100[i]
Transmission interconnection capital [USD/MW/km] (c_i)	450[j]	450[j]	450[j]
Transmission interconnection fixed O&M [USD/km] ($o_{f,i}$)	-	-	-
Substation capital [USD/MW] (c_s) (for 2 substations)	70,000[j]	70,000[j]	70,000[j]
Road capital [USD/km] (c_r)	407,000[k]	407,000[k]	407,000[k]
Road fixed O&M [USD/km] ($o_{f,r}$)	-	-	-
Economic discount rate (i)	7%[l]	7%[l]	7%[l]
Lifetime [years] (n)	25[m]	25[m]	25[m]

[a] Applied 75% land-use discount factor to higher land-use factor to account for greater spread of wind turbines and uncertainties in land availability for all technologies [33].
[b] Assumption used by National Institute of Wind Energy, India [19] and [22].
[c] Mean of U.S. empirical values [29]
[d] Estimated from no-storage land use factor by multiplying by the ratio of no-storage to 6-hr-storage solar multiples (2.1/1.2).
[e] [34]
[f] System Adviser Model (SAM) [32]
[g] Capital costs estimated using 2017-18 auction prices as benchmarks.
[h] Capital costs derived from IRENA 2017 estimates for CSP with 4-8 hour storage [3].
[i] O&M costs from IRENA 2017 estimates [3].
[j] Average of 132 kV, 220 kV, and 400 kV transmission line and substation costs [35].
[k] [36] Costs are for two lane bituminous road, and inflation adjusted.
[l] Average real interest rate from 2014-16 for India from The World Bank [7]
[m] [37]

suitable CSP resource areas using hourly DNI data in the System Advisor

Model [32].[6] We then chose to fit a logarithmic equation to the CFs and average DNI data because of known increased efficiency losses at the higher end of the DNI range (Figure C.11 in SI C). Using the fitted logarithmic curve equation (Eq. 1, $R^2 = 0.998$) and spatially averaged DNI, we estimated CFs for a 6-hr-storage CSP power plant for each POA.

$$cf_{CSP} = 0.369 \cdot ln\,(DNI) - 0.225 \tag{1}$$

Wind. The CF of a wind turbine depends on wind speed distribution at the turbine hub height, air density, and the turbine power curve. In this analysis, we estimated CFs from wind speeds at a turbine hub height of 80 m.

On-shore wind turbines are generally classified into three International Electrotechnical Commission (IEC) classes depending on the wind speed regimes. We used normalized wind turbine power curves for the three IEC classes developed by NREL [39] and scaled them for a 2000 kW rated turbine. For each of the three turbine classes, we adjusted the power curves for the entire range of possible air densities (0.775-1.275 kg/m^3 in 0.5 kg/m^3 increments) by scaling the wind speeds of the standard curves according to the International Standard IEC 61400-12 [40, 41].

To compute the CF for each 3.6 km grid cell (the native resolution of Vaisala data), we used methods described in [26]. We first assigned IEC classes based on each grid cell's annual average wind speed [42]. Second, to account for the effect of air density on power generation, we estimated the air density using elevation and average annual temperature for each grid cell. We then selected the appropriate air-density-adjusted power curve given the average wind speed, which determines the IEC class, and the air density, which determines the air-density adjustment within the IEC class. For each grid cell, we discretely computed the power output at each wind speed given its probability (using a Weibull distribution with a shape factor of 2) and summed the power output across all wind speeds within the turbines operational range to calculate the mean wind power output ($\overline{P}$). The capacity

[6] The DNI solar resource data for India were developed by NREL using satellite imagery and a numerical model developed at the State University of New York (SUNY) with the weather data from the Integrated Surface Database maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA).

factor (cf_{wind}) is simply the ratio of the mean wind power output to the rated power output of the turbine (P_r or 2000 kW), accounting for any collection losses (η_a) and outages (η_o) (Eq. 2).

$$cf_{wind} = \frac{(1 - \eta_a) \cdot (1 - \eta_o) \cdot \overline{P}}{P_r} \tag{2}$$

2.2.2. Levelized Cost of Electricity (LCOE) estimation

LCOE is the average cost of electricity for every unit of electricity generated over the lifetime of a project at the point of interconnection. Using the economic and technical parameters listed in Table 3 and the CFs and distances to nearest substation and road estimated for each POA, we calculated the generation, interconnection and road components of the levelized cost of electricity (LCOE in USD/MWh) (equations 3, 4, 5). The total LCOE is simply the sum of the generation, transmission, and road cost components.

Rapidly changing economics of wind and solar PV technologies makes it difficult to accurately estimate average capital costs. Thus, for determining capital costs of these two technologies, we used recent auction prices for RE in India as benchmarks. From Jan 2017 to Jan 2018, 5.2 GW of solar PV capacity and 5 GW of wind capacity was procured through various state and central government auctions. For the auction-winning project, we first assumed a nominal CF at the 90th percentile of all POA's annual average CFs. Using this CF along with assumptions for fixed operations and maintenance (O&M) cost, discount rate, and plant lifetime (Table 3) and the capacity-weighted mean auction price in equation 3 provided us with a nominal capital cost for each technology (Table 3; rounded to two significant figures). The generation LCOE for each POA was then estimated using the capacity factor for that POA, the nominal capital cost, and assumptions for fixed O&M costs, discount rate, and lifetime (Table 3) in equation 3.

We derived the average capital cost for CSP with 6 hour storage from estimates provided by [3]. However, capital costs of CSP vary significantly because of a wide variation in technology among plants, e.g. type of collectors and receivers, single or double axis tracking, and amount and type of storage. Commercial CSP plants are also few in number, with limited public data on costs. Hence, our estimates are subject to significant uncertainties.

For transmission and road costs, we estimated distances of POAs from nearest high-voltage substation (220 kV and above) and nearest road. To account for terrain and other development constraints that would dictate the actual path of the extended road or transmission line, we then applied a terrain factor of 1.3 to the estimated distances.

We calculated the capital cost of transmission as a function of its length alone, holding all other cost parameters constant. To this cost, we added the cost of the substations, which does not vary by distance (see Table 3 for parameter values). We then used this total capital cost to estimate the transmission interconnection component of the LCOE using equation 4.

Road LCOE was estimated using a fixed capital cost per km of additional road needed to service the project, and is expressed per unit of electricity output from the project (equation 5). Road costs can vary widely depending on the type of road, terrain, and region-specific factors such as labor costs and financing. We assumed costs for a two lane bituminous road (Table 3). We also assumed that one road will be built for every 50 MW capacity project, which is a reasonable size for a utility-scale project.

$$LCOE_{generation,t,x} = \frac{(c_{g,t} i_{cr} + o_{f,g,t})}{8760 \cdot r_{t,x}} \tag{3}$$

$$LCOE_{interconnection,t,x} = \frac{(d_{i,x} (c_i i_{cr} + o_{f,i}) + c_s i_{cr})}{8760 \cdot r_{t,x}} \tag{4}$$

$$LCOE_{road,t,x} = \frac{d_{r,x} (c_r i_{cr} + o_{f,r})}{8760 \cdot r_{t,x} \cdot 50MW} \tag{5}$$

$$i_{cr} = \frac{i (1+i)^n}{(1+i)^n - 1} \tag{6}$$

Where $c_{g,t}$ is the capital cost of generation for technology t; c_i is the capital cost of transmission interconnection (i); c_s is the capital cost of two substations (s); c_r is the capital cost of road; $r_{t,x}$ is the capacity factor of technology t and POA x; $o_{f,g,t}$ is the fixed operations and maintenance cost of generation for technology t; $o_{f,i,t}$ is the fixed operations and maintenance cost of interconnection (i) for technology t; $o_{f,r}$ is the fixed (f) operations and maintenance cost of roads (r). The capital recovery factor (i_{cr}) converts a present value to a uniform stream of annualized values given a discount rate and the number of interest periods (Eqn. 6). n is the number of years in the lifetime of a power plant.

To address evolving cost assumptions, we examined the sensitivity of total LCOE to key parameters by varying values of those parameters within realistic ranges. We used median, minimum, and maximum estimates for CFs and distances to nearest road and substation as base case and minimum and maximum limits for the sensitivity analysis. We derived the range of capital costs from India's highest and lowest auction prices in 2017-18 for wind and solar PV, and varied CSP capital costs by 20%. We varied the real discount rate by 3 percentage points from the base value of 7%. The remaining parameters were varied by 20% of their base value. We did not include land costs because of lack of data.

2.2.3. Other attributes

We estimated the following additional attributes for each POA that inform the constraints to and opportunities for RE development: overlap with agricultural cropland, water stress level, and potential for co-location with another RE technology. To evaluate potential conflict of RE development with agriculture, wind POAs located in agricultural areas were identified by their overlap with any of the six cropland land-use land-cover categories of the NRSC data - kharif, rabi, zaid, double/triple, current fallow, and shifting cultivation (Table 1; [43]). Agricultural lands are excluded from solar suitable areas in this study.

Water availability is crucial for solar PV and CSP plants. CSP technologies using recirculating evaporative cooling tower, one of the most widely used cooling technologies in thermal power plants, consume the most water (3000-3800 liters/MWh) [44] among RE technologies considered in this study. Dry-cooled CSP plants could reduce water consumption significantly to 100-300 liters/MWh [44], but these plants have higher costs and lower efficiencies compared to evaporative cooling technologies. Utility-scale solar PV power plants, on average, require about 100 liters/MWh [44], mainly for cleaning panels to prevent soiling [45], which is much lower than CSP plants, but is still significant in water-stressed areas. Wind plants have insignificant water use requirements.

To assess the vulnerability of solar plants to water scarcity, we overlaid the water-stressed areas identified in the World Resources Institute's (WRI)

Aqueduct Water Atlas using estimates of Baseline Water Stress (BWS) or relative water demand [12]. We focused on the "Extremely High Stress" and "High Stress" areas, where annual water withdrawal is >80% and 40%-80% of blue water or surface water availability respectively.

Co-locating wind and solar PV plants can enable greater land and transmission utilization, especially when the temporal profiles of generation from the two technologies are complementary. To estimate the potential for co-locating two RE technologies, we simply identified POAs with overlapping wind and solar resources. We limited this analysis to only wind and solar PV technologies because PV panels can occupy areas between wind turbines.

3. Results

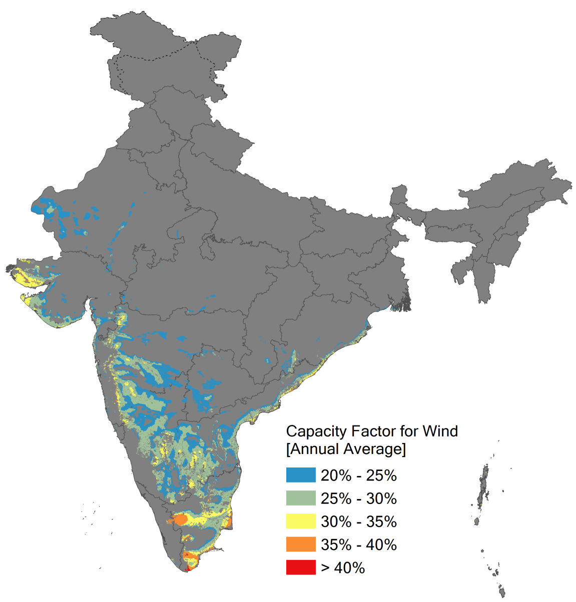
3.1. Technical potential of wind and solar resources

Abundant wind, solar PV, and CSP potential exists within India. These resources, however, are distributed unevenly across the country. Because RE targets are set by state-specific policies and states are the first tier of balancing areas in India's interconnected national electricity grid, we use the state as the sub-national geographical unit of analysis to present our results. See Tables 4, 5, 6 for the technical potential in each state.

India's wind energy generation potential is greater than three times its annual energy demand forecast for 2030 [8] assuming a land-use factor of 9 MW /km^2. If a land-use factor of 2.25 MW /km^2 is assumed (lowered to account for uncertainties and ground-realities not captured in geospatial data), the wind potential is about 80% of the 2030 energy demand forecast. Wind resources are concentrated mainly in the western states (Gujarat, Maharashtra, and Rajasthan) and southern states (Andhra Pradesh, Karnataka, Tamil Nadu, and Telangana), together accounting for over 95% of total wind potential (Table 4, Figure 2). The highest quality resources are concentrated in Tamil Nadu and Gujarat.

Table 4: State-wise technical potential for electricity generation and capacity for wind

		Land use factor: 9 MW/km^2		Land use factor: 2.25 MW/km^2	
State	**Area (km^2)**	**Generation Potential (TWh)**	**Capacity Potential (GW)**	**Generation Potential (TWh)**	**Capacity Potential (GW)**
Andhra Pradesh (AP)	64,000	1,300	580	330	150
Chhattisgarh (CT)	840	16	8	4	2
Gujarat (GJ)	35,000	760	320	190	79
Karnataka (KA)	89,000	1,800	800	450	200
Kerala (KL)	910	24	8	6	2
Madhya Pradesh (MP)	2,300	42	21	10	5
Maharashtra (MH)	77,000	1,600	690	390	170
Odisha (OD)	8,000	160	72	40	18
Rajasthan (RJ)	23,000	430	210	110	52
Tamil Nadu (TN)	60,000	1,400	540	350	140
Telangana (TG)	15,000	270	130	67	33
India Total	376,000	7,800	3,400	2,000	850



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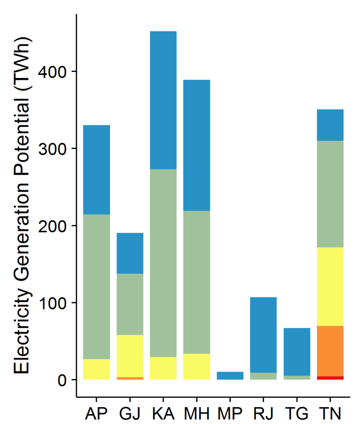


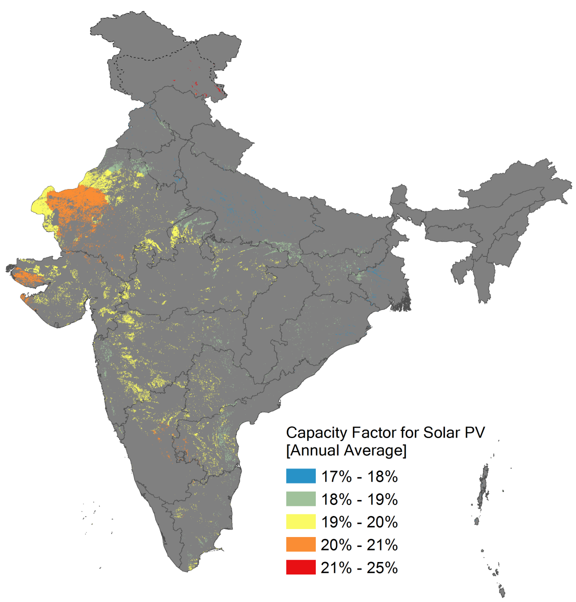
(b)

Figure 2: Spatial distribution (a) and state-wise potential (b) of wind electricity generation for a range of annual capacity factors, estimated for wind turbines with 80m hub heights. Wind speed resource threshold is 5.5 m/s and land use factor is 2.25 MW/km^2.

Total solar PV energy generation potential for utility-scale power plants with expected capacity factors of at least 17% is greater than four times India's energy demand forecast for 2030 [8] assuming a land-use factor of 30 MW /km^2 (Table 5, Figure 3). If a land-use factor of 7.5 MW /km^2 (lowered to account for uncertainties) is assumed, this potential is similar to the 2030 forecast of total electricity demand. While solar PV resources are distributed across several states, the five states of Rajasthan, Gujarat, Maharashtra, Madhya Pradesh, and Andhra Pradesh account for over 80% of these resources. Almost half the solar PV resources are located in Rajasthan alone. Solar PV resources in the rest of India are limited primarily because of constraints on land use (e.g. agricultural land) and slope rather than poor resource quality. This is evident from the relatively few areas with capacity factors below 18% (Figure 3).

Table 5: State-wise technical potential for electricity generation and capacity for solar PV.

		Land use factor: 30 MW/km^2		**Land use factor: 7.5 MW/km^2**	
State	**Area (km^2)**	**Generation Potential (TWh)**	**Capacity Potential (GW)**	**Generation Potential (TWh)**	**Capacity Potential (GW)**
Andhra Pradesh (AP)	10,100	510	300	130	76
Bihar (BR)	750	36	22	9	6
Gujarat (GJ)	20,200	1,100	610	260	150
Haryana (HR)	1,300	61	38	15	10
Jammu & Kashmir (JK)	570	33	17	8	4
Jharkhand (JH)	1,500	72	44	18	11
Karnataka (KA)	4,700	240	140	61	35
Madhya Pradesh (MP)	14,400	720	430	180	110
Maharashtra (MH)	20,400	1,040	610	260	150
Odisha (OD)	2,100	100	62	25	15
Punjab (PB)	770	37	23	9	6
Rajasthan (RJ)	80,300	4,200	2,400	1,000	600
Tamil Nadu (TN)	3,500	180	100	44	26
Telangana (TG)	4,300	220	130	55	32
Uttar Pradesh (UP)	5,400	260	160	64	40
Uttarakhand (UT)	300	14	9	4	2
West Bengal (WB)	1,800	87	55	22	14
India Total	173,000	8,900	5,200	2,200	1,300



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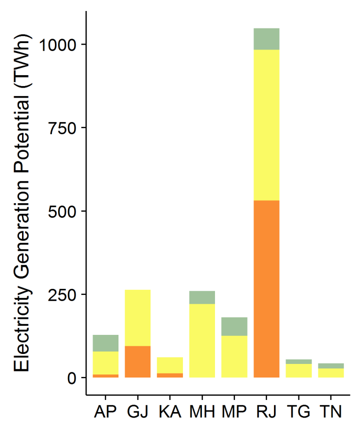


(b)

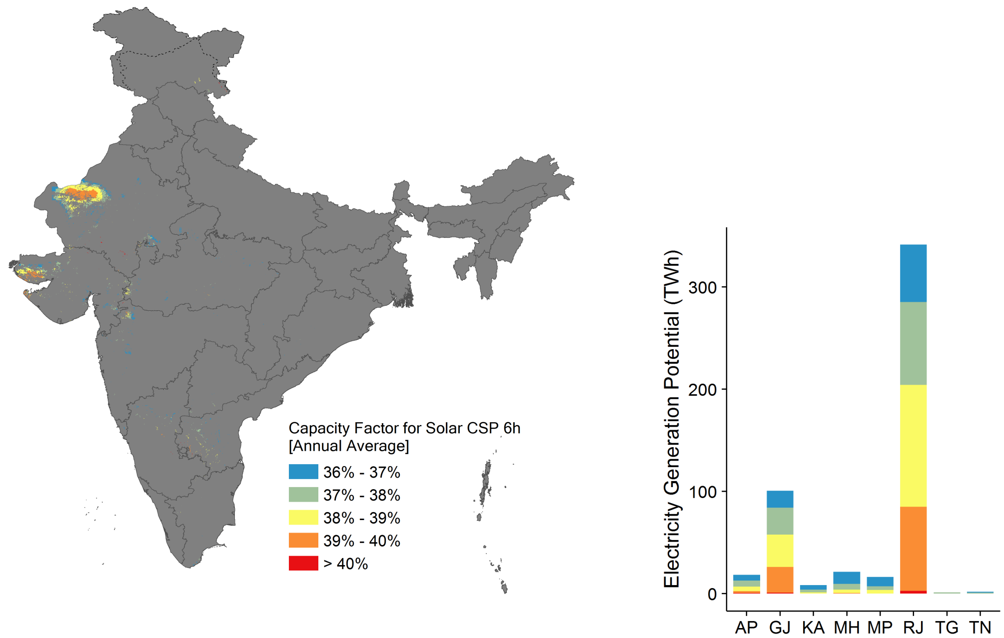
Figure 3: Spatial distribution (a) and state-wise potential (b) of solar PV (fixed tilt) electricity generation for a range of annual capacity factors, estimated for fixed-tilt systems. Global Horizontal Irradiance (GHI) resource threshold is 4.9 kWh/m^2-day and land use factor is 7.5 MW/km^2.

CSP resources are the most limited amongst the three technologies and naturally closely follow the pattern of solar PV spatial distribution. Total energy generation potential for CSP plants with 6-hour storage that have expected annual capacity factors greater than 36% is about four-fifths of India's 2030 energy demand forecast assuming a land-use factor of 17 MW/km^2 and only a fifth of this demand forecast if a land-use factor of 4.25 MW/km^2 is assumed (Table 5, Figure 3).

CSP potential is highest in Rajasthan, Gujarat, Maharashtra, Andhra Pradesh, and Madhya Pradesh (Table 6, Figure 4). More than 60% of CSP resources lie in Rajasthan. While areas in the Ladakh district of Jammu and Kashmir have the highest resource quality (i.e., highest DNI), development potential in this state is limited due to protected areas and hilly topography considered unsuitable for CSP development.

Table 6: State-wise technical potential for electricity generation and capacity for Concentrated Solar Power with 6-hour storage

		Land use factor: 17 MW/km^2		**Land use factor: 4.25 MW/km^2**	
State	**Area (km^2)**	**Generation Potential (TWh)**	**Capacity Potential (GW)**	**Generation Potential (TWh)**	**Capacity Potential (GW)**
Andhra Pradesh (AP)	1,300	70	22	18	6
Gujarat (GJ)	7,100	400	120	100	30
Jammu & Kashmir (JK)	310	19	5	5	1
Karnataka (KN)	640	35	11	9	3
Madhya Pradesh (MP)	1,200	66	20	16	5
Maharashtra (MH)	1,600	87	27	22	7
Rajasthan (RJ)	24,000	1,400	410	340	100
Tamil Nadu (TN)	140	8	2	2	1
Telangana (TG)	100	6	2	1	1
India Total	36,400	2,100	620	520	160



(a) (b)

Figure 4: Spatial distribution (a) and state-wise potential (b) of solar CSP (with 6-hour storage) electricity generation for a range of annual capacity factors, estimated for plants with 6-hour storage. DNI resource threshold is 4.9 kWh/m^2-day and land use factor is 4.25 MW/km^2.

3.2. Costs

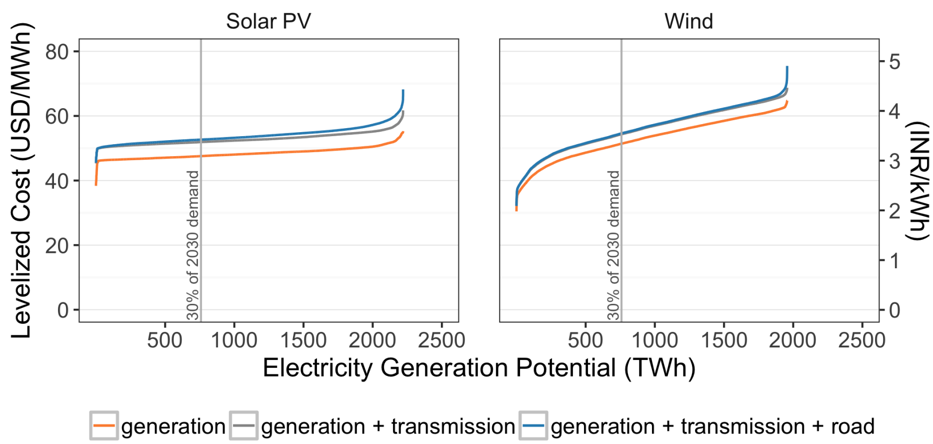
Assuming capital costs derived from mean auction prices, the 5th and 95th percentiles of generation LCOE estimates range from USD 47-52 per MWh (INR 3.0-3.4 per kWh) for solar PV (GHI resource quality > 4.9 kWh/m^2-day) and USD 42-62 per MWh (INR 2.7-4.0 per kWh) for wind (wind speed resource quality > 5.5 m/s). For CSP, assuming capital costs derived from [3], the 5th and 95th percentiles of generation LCOE estimates range from USD 215-234 per MWh (INR 14-15 per kWh) for CSP (DNI resource quality > 4.9 kWh/m^2-day).

Figure 5a shows that generation LCOEs for solar PV and wind have overlapping distributions. On a levelized cost basis, solar PV and wind are economically competitive with each other. For better clarity of solar PV and wind LCOE supply curves, CSP LCOEs, which are significantly greater, are shown separately in Figure B.10. CSP is 3 to 5 times more expensive than both solar PV and wind. CSP cost assumptions are likely to have large uncertainties because of limited number of commercial projects and significantly diverse technologies within CSP.

The 5th and 95th percentiles of transmission costs are USD 4-5 per MWh (7-11% of generation LCOE) for solar PV, USD 2-4 per MWh (5-7% of generation LCOE) for wind, and USD 2-3 per MWh (1-2% of generation LCOE) for CSP. Higher transmission costs for solar PV reflect the relatively sparse substation infrastructure in good but remote solar resource areas of Rajasthan and Gujarat. Although CSP sites overlap with and are a subset of solar PV sites, transmission costs on a levelized basis are lower for CSP with storage because of its relatively higher capacity factors compared to solar PV, demonstrating the effect of storage in increasing transmission utilization. High density of roads result in relatively low road costs with median values of less than USD 0.5 per MWh across all technologies.

An important question for scaling up RE is how much its costs will increase as lower resource quality sites are developed with greater deployment of solar PV plants and wind turbines. The greater distribution of wind LCOEs reflects the greater variability in wind quality across the country, whereas lower variation in solar GHI resource quality results in similar LCOEs across solar PV resource areas (See Figure 5a). Therefore, assuming no technology advancement or cost reduction, marginal wind LCOEs are likely to increase much more compared to the rise in marginal solar PV LCOEs as more wind and solar plants are installed.

We conducted sensitivity analysis as outlined in the Methods section. Total LCOE is most sensitive to three parameters: capacity factor, which depends on the resource quality at a project site; capital costs, which evolve through technological advances, economies of scale, and learning by doing; and discount rate, which is a reflection of financing rates available in a region (See Figure 5b). The total LCOE is also sensitive to distances to nearest road and substation, which suggests prioritizing sites close to roads and transmission infrastructure will keep costs low.



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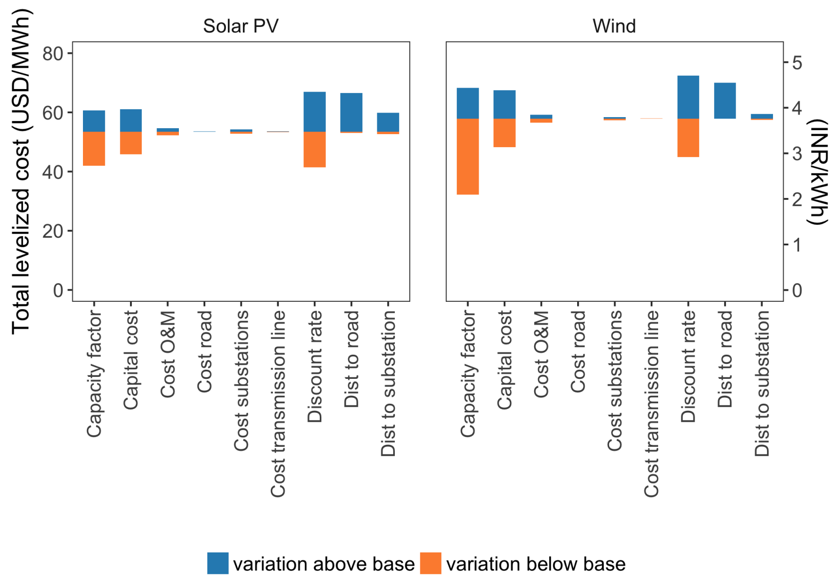


(b)

Figure 5: (a) Electricity generation potential and levelized cost of electricity estimates for generation, transmission, and road for solar PV and wind and (b) total levelized cost of electricity sensitivity to multiple parameters. For sensitivity analysis, maximum, median (base), and minimum values for capacity factors and distances to nearest substation and road are estimates from this analysis; capital cost ranges are derived from lowest and highest 2017-18 auction prices; discount rate is varied from 4% to 10%; other parameters varied by +/- 20% of base values (Table 3).

3.3. Access to transmission infrastructure

Project opportunity areas that are farther from the nearest transmission infrastructure will incur higher interconnection costs. Karnataka, Maharashtra, Tamil Nadu, and Telangana are the best states for access to transmission infrastructure in terms of proximity to existing substations. In these states, for both solar PV and wind, between 50-60% of potential capacity is within 25 km and more than 90% of resources are within 50 km of a high-voltage (> 220 kV) substation, indicating high accessibility of renewable resources to transmission infrastructure (Figure 6).

In the states of Gujarat, Rajasthan, Andhra Pradesh, and Madhya Pradesh, strategic investments in transmission infrastructure will enable access to high quality solar and wind resources. While Gujarat's wind resources have high accessibility to transmission networks, for solar resources, only 40-45% are within 25 km and 80% are within 50 km of a high-voltage substation.

In Rajasthan, only 20% of solar and 30% of wind resources are within 25 km distance from the nearest high-voltage substation (Figure 6). For resources within 50 km distance to nearest substation, these shares increase to 60% for solar and 75% for wind. While the total solar PV resources that are near high-voltage substations are abundant, lack of transmission infrastructure may hamper development of wind and CSP resources in Rajasthan. Finally, access to transmission is likely to be a constraint in Andhra Pradesh and Madhya Pradesh, with less than 50% RE resources located within 25 km of a high-voltage substation.

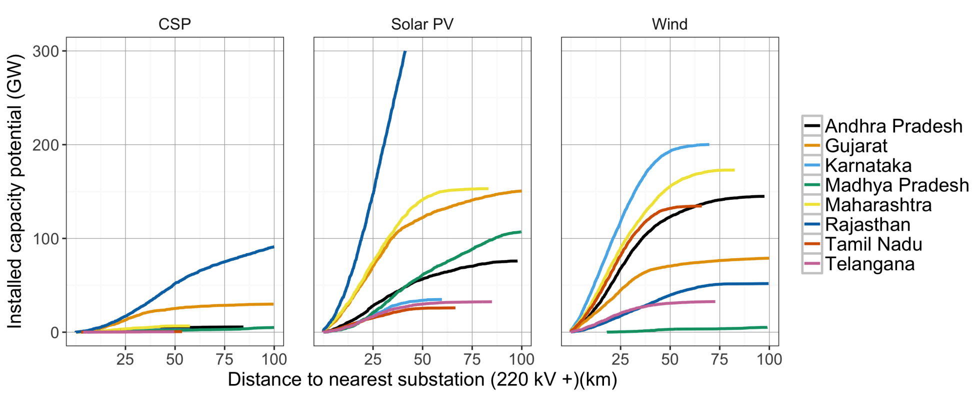


Figure 6: Proximity of concentrated solar power (CSP), solar PV, and wind resources to high-voltage transmission substation infrastructure. Axes are cut off at 100 km and 300 GW

3.4. Agriculture and wind power development

In India, 84% of wind resources are located on agricultural lands (Figure 7). As classified by the NRSC land use land cover data, these areas include agricultural lands with single and multiple planting seasons as well as those that are fallow and experience shifting cultivation (Table 1 for land classification). Of all states, Rajasthan and Gujarat have the largest percentage of wind resources on non-agricultural areas. These areas include the Kutch region of Gujarat and desert regions in Rajasthan. More than three-quarters of wind resources in other wind-rich states lie on agricultural lands.

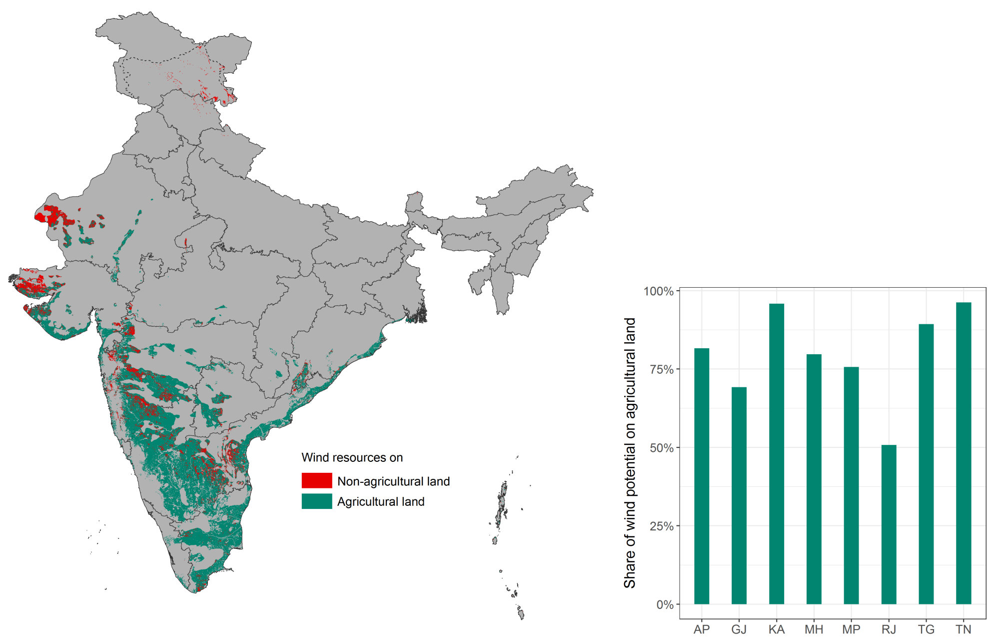


Figure 7: (a) Wind resources on agricultural and non-agricultural lands identified using land use and land cover data from India's National Remote Sensing Center. (b) Share of wind resources on agricultural land.

3.5. Water stress and solar power development

Across India, 71% of CSP resources are in "Extremely High Water Stress" areas and a further 17% are in "High Stress" areas as defined by WRI's Aqueduct Water Atlas. For solar PV, 57% and 22% of resources are in "Extremely

High Stress" and "High Stress" areas, respectively. In the state of Rajasthan, which contains almost half the country's identified solar PV potential and more than 60% of CSP potential, almost all the potential project areas are under extremely high water stress (Figure 8). This highlights the severe vulnerability of solar resources to water scarcity in India.

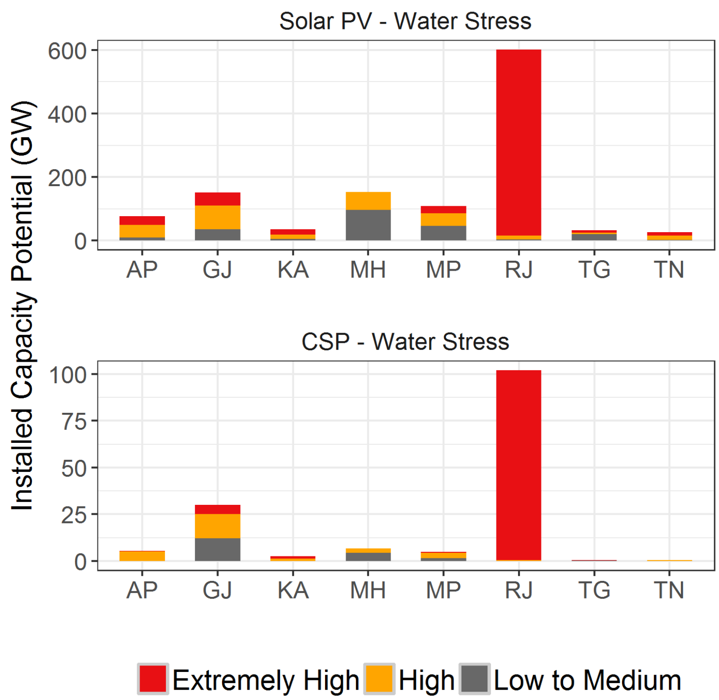
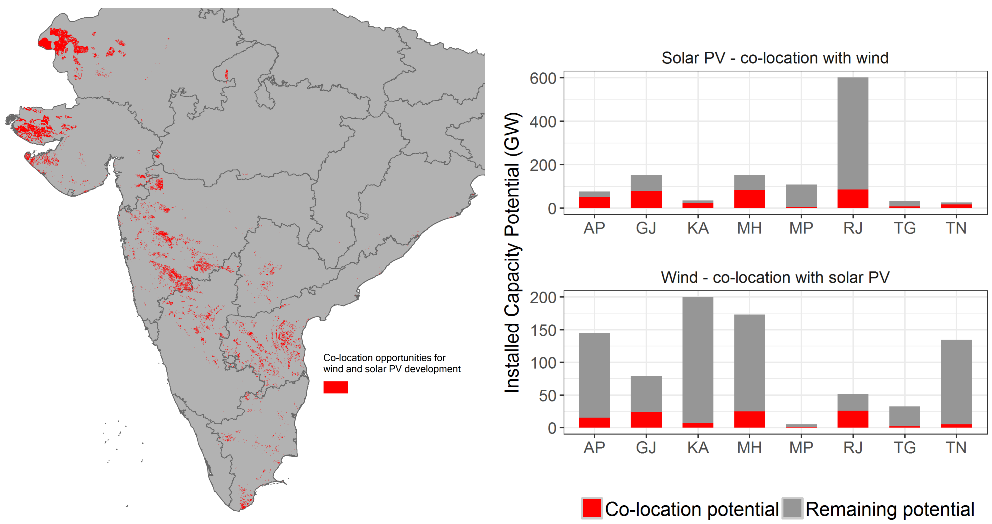


Figure 8: Water stressed resources for solar PV and concentrated solar power (CSP).

3.6. Co-locating wind and solar PV plants

We found approximately 48,000 km^2 of area suitable for co-location of wind and solar PV plants (Figure 9a). Assuming lower estimates of land-use factors - 2.25 MW/km^2 for wind and 7.5 MW/km^2 for solar PV, these areas could accommodate 110 GW of wind capacity (or 13% of total wind potential) and 360 GW of utility-scale solar PV capacity (or 28% of total solar PV potential). These co-located wind and solar PV power plants could generate an estimated 25% and 10% of electricity demand in 2030, respectively. Assuming the four times greater (non-discounted) land-use factors for both wind and solar PV, wind-solar PV hybrid plant potential exceeds the electricity demand in 2030.

Because we excluded croplands from suitable solar resource areas, areas suitable for co-location do not include agricultural areas. Non-agricultural lands with suitable wind resources are almost always suitable for solar PV deployment except when slope is greater than 5%. Andhra Pradesh, Gujarat, Maharashtra, and Rajasthan have greatest potential for co-location.



(a) (b)

Figure 9: (a) Co-location opportunities for wind and solar PV projects. (b) Wind and solar PV co-location opportunity potential as a share of total potential in major renewable energy states.

4. Discussion

4.1. Uncertainties in potential estimates

Our estimates of RE resources differ from other studies because of differences in mesoscale resource input data sets, exclusion areas including land-use and land-cover input data and categories, and land-use factors. Assuming the same land-use factor, our wind potential estimate is similar to previous studies [22, 14, 15]. The official Government of India estimate of wind potential is an order of magnitude smaller (102 GW) because of a significantly low land-use factor assumption compared to this study [19], in addition to different resource input data. For both solar technologies, potential estimates in previous studies [19, 21] are likely exaggerated due to higher land-use factor assumptions, which are not based on empirical estimates unlike this study.

Technology assumptions (e.g. fixed tilt, single or dual axis tracking for solar PV; turbine power curves and hub heights for wind; parabolic trough or central tower with or without storage for CSP) also affect potential estimates [25, 46]. Actual developable potential is limited by ground realities such as land ownership and conflict areas, which are difficult to capture in geospatial analysis. In spite of these uncertainties, RE resources identified and estimated through geospatial analysis are useful for policymaking and understanding the spatial distribution of these resources across regions. Better ground-validated and bias-corrected data sets will improve the accuracy of such analyses.

4.2. Economics of solar and wind

Levelized costs of both wind and solar PV technologies have rapidly declined over the last decade. Cost of solar PV generation fell by almost three-quarters in 2010-2017 due to technological advancements and economies of scale [3]. Costs of wind generation are also declining as wind turbines with higher hub heights allow these machines to harness faster wind speeds, and larger rotor diameters capture more energy at the same sites without incurring a proportional increase in costs [47]. Auction-based energy generation procurements have allowed governments such as India's to capture these cost reductions by encouraging competition [3]. Our estimates of solar PV and wind LCOEs, anchored to India's 2017-18 auction prices, are at the lower end of the 2017 LCOE range estimates by IRENA [3].

On a levelized cost basis, wind and solar PV generation is increasingly cost competitive with coal generation in India [4]. More than 85% of 141 GW coal capacity was more expensive than USD 38 per MWh, the minimum realized auction price for both wind and solar PV in 2017-2018 [48, 49, 50], which is at the lower end of our LCOE estimates.[7]

[7] Fixed and variable costs for coal generation are from Ministry of Power's Merit Order Despatch of Electricity for Rejuvenation of Income and Transparency website accessed in June 2018. Solar PV auction winning bid of INR 2.47 per kWh (USD 38 per MWh) is from Solar Energy Corporation of India's (SECI) December 2017 auction in Bhadla, Rajasthan. Wind auction winning bid of INR 2.44 per kWh (USD 38 per MWh) is from

We found that marginal RE resource quality for wind will worsen as more plants are installed. In contrast, solar resource quality varies relatively less across India. However, costs and prices of both wind and solar PV will likely continue to improve with technology advancements, economies of scale, and market dynamics.

Because LCOEs for wind and solar PV are sensitive to multiple factors, estimates in this study should be interpreted as only indicative. Actual costs at a site depend on project-specific factors including but not limited to on-the-ground measurement of resources, capital costs of equipment, and financing rates.

System integration costs or costs incurred due to variability and uncertainty of RE generation are not included in our analysis. Further, an LCOE does not reflect the economic value of RE generation, which depends on the timing and location of generation and the marginal avoided costs to the overall system [51]. The marginal economic value of both wind and solar PV resources decreases as their share of overall energy generation increases [52] and is an important area of future research.

4.3. Transmission planning

Lack of high-voltage transmission infrastructure in high quality RE resource areas may either deter new RE development or lead to a high number of low-voltage low-capacity transmission lines from installations to pooling substations, which would result in greater land fragmentation and environmental impact [53]. Because of their lower capacity to transmit energy, low-voltage transmission lines are likely to experience more congestion than high-voltage lines when their transmission limits are violated. During such congestion events, system operators are forced to curtail RE generation and project developers may bear the resulting financial losses. Early planning and expanding high-voltage transmission infrastructure in RE resource areas or zones will not only lower costs of interconnection for project developers, but also reduce the probability of transmission congestion. Successful examples of RE zoning initiatives include Texas' Competitive Renewable Energy Zones [11, 54] and South Africa's Renewable Energy Development Zones [55].

The Government of India's Green Corridors plan has also focused on building high-voltage transmission infrastructure to evacuate RE generation

SECI's February 2018 auction all India auction.

[35]. However, the study used only near-term siting plans of project developers and not spatially-explicit renewable resource and environmental data as input to transmission planning studies. Combining spatial data of suitable RE sites with project developer siting plans will enable a more robust, stakeholder-driven transmission planning process.

We use only proximity to substations as an indicator for access to transmission. Given data availability, RE resource areas closer to substations that have greater margins for evacuating energy should be prioritized. Only physical access to the interconnection point may not mean adequate capacity for the transmission network to absorb the additional RE generation because other parts of the electricity network may experience congestion. Comprehensive power flow analyses and transmission planning studies are essential to plan new RE plants.

4.4. Multiple criteria for planning

Incorporating multiple criteria including social and environmental criteria in addition to economic criteria would enable economically competitive, low-environmental-impact, and socially beneficial renewable resources to contribute toward meeting India's future electricity demand. This study focused on minimizing conflict with agriculture and encouraging dual use for wind power development, avoiding solar power deployments in water stressed areas and employing strategies to minimize water usage, and pursuing opportunities for co-locating wind and solar power plants.

Understanding constraints to RE development would prompt mitigation actions. For example, robotic dry cleaning systems [56] and emerging technologies such as hydrophobic nanocoatings and electrostatic curtains for solar PV panels [57] could limit water usage in water-stressed regions. Dry-cooling in CSP plants have the potential to reduce water consumption by more than 90% [44], although greater efficiency losses would affect the economics of the plant. Because the direct land footprint of a wind turbine is small (5-10%) relative to the entire area of a wind farm [58], dual use of the land for farming and wind generation is not only possible, but preferable to increase land-use efficiency and avoid environmental impacts from greenfield development projects. The large wind potential in agricultural areas offers the opportunity for the agricultural community to earn revenues from energy generation, which could be facilitated through socially-equitable policies that encourage cooperative-ownership, land leasing, and revenue-sharing.

Additional criteria that may improve planning of RE resources include socio-economic parameters like local gross domestic product, employment rate, and basic infrastructure; economic parameters such as capacity value, which depends on the coincidence of RE generation with peak electricity prices; and environmental indicators such as biodiversity value, bird and bat habitats, and human footprint. Multi-criteria planning of RE resources will avoid conflict, increase co-benefits, and accelerate deployment of RE [26, 59].

5. Conclusions

We identify abundant renewable resources in India – 850-3,400 GW for wind, 1,300-5,200 GW for solar PV, 160-620 GW for CSP. Just the lower estimates of wind and solar PV resources could each generate energy almost equivalent to India's expected 2030 demand. But these resources are geographically unevenly distributed, and are concentrated in western and southern states—Tamil Nadu, Maharashtra, Gujarat, Rajasthan, Andhra Pradesh, Telangana, Karnataka, and Madhya Pradesh—which collectively will have a share of 55 percent of India's expected electricity demand in 2030 [8]. The spatial unevenness of RE resources underscores the importance of inter-regional transmission lines and sharing of balancing resources across the entire grid to ensure cost-effective and reliable integration of high shares of variable RE generation.

Deriving capital costs from 2017-18 auction prices in India, we estimate the 5th and 95th percentiles of generation LCOE ranging from USD 47-52 per MWh for solar PV and USD 42-62 per MWh for wind, similar to the lower end of IRENA's 2017 global cost estimates. Assuming capital costs from [3] for CSP, the 5th and 95th percentiles of our estimates of generation LCOE range from USD 215-234 per MWh, which are 3-5 times greater than those for wind and solar PV. Levelized costs of generation for wind and solar PV overlap significantly but they vary much more across wind resource areas than those across solar areas because of greater heterogeneity in the quality of wind resources compared to that of solar. LCOE estimates are most sensitive to capital cost, capacity factor, and discount rate.

Karnataka, Maharashtra, Tamil Nadu, and Telangana are the best states in terms of proximity of RE resources to existing high-voltage substations. Transmission investments in Gujarat, Rajasthan, Andhra Pradesh, and Madhya Pradesh are needed to help harness significant renewable resources. Identifying high quality resource areas for pre-planning of high-voltage transmission infrastructure will encourage RE development and avoid long-distance low-voltage transmission interconnections that often result in congestion and land fragmentation.

More than 80% of India's wind resources lie on agricultural lands where dual land use strategies could encourage wind development, avoid loss of agriculturally productive land, and increase land use efficiency. Approximately 90% of CSP resources and 80% of solar PV resources are in areas experiencing high water stress, severely restricting development of solar plants, unless their water requirements are minimized. We find co-location potential of at least 110 GW of wind and 360 GW of solar PV, which together could meet 35% of India's electricity demand in 2030. Incorporating multiple criteria in spatial planning will help identify constraints and harness opportunities to rapidly scale up wind and solar development.

Declaration of Interest

None

Acknowledgements

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A. Supplementary Information: Data sources and resource assessment thresholds

Table A.7: **Data sources and resource assessment thresholds**

Stage of analysis	Category	Source	Description	Year	Default exclusion thresholds
Resource assessment	Boundaries	Global Administrative Database (GADM) v2	GADM is a spatial database of the location of the world's administrative areas (or administrative boundaries) including countries and lower level subdivisions.	2012	
Resource assessment	Boundaries	Ministry of New and Renewable Energy	The Ministry of New and Renewable Energy of India published a map of the state and district boundaries of India as part of its solar resource assessment.	Unknown	
Resource assessment	Elevation	Shuttle Radar Topographic Mission (SRTM) CGIAR-CGI Digital Elevation dataset v4.1	Originally produced by NASA, the SRTM is a high quality digital elevation dataset for large portions of the tropics and other areas of the developing world, and has a resolution of 3 arc seconds (approx. 90 m).	2000	>5000 m (all technologies)
Resource assessment	Slope	SRTM - CGIAR	Created from elevation dataset using ArcGIS Spatial Analyst.	2000	>5% (solar); >20% (wind)
Estimation of Project opportunity area attributes	Temperature	WorldClim	WorldClim is a set of global climate layers (climate grids) with a spatial resolution of about 1 square kilometer (Hijmans et al. 2005). http://www.worldclim.org/formats	1950 - 2000	
Resource assessment	Land use/land cover (LULC)	NRSC of India	Developed by the National Remote Sensing Centre of the Indian Space Research Organisation, this land use-land cover dataset is provided at a scale of 1:50,000. Overall accuracy of different LULC classes can vary from 79% (agro-horticulture) to 97% (waterbodies).	2010-11	See Table 1

Stage of analysis	Category	Source	Description	Year	Default exclusion thresholds
Resource assessment and Project opportunity area attributes	Water bodies	World Wildlife Federation Global lakes and wetlands database	Comprises lakes, reservoirs, rivers and different wetland types in the form of a global raster map at 30-second resolution. Exclusion categories in this analysis include: lake, reservoir, river, freshwater marsh, floodplain, swamp forest, flooded forest, coastal wetland, brackish/saline wetland, and intermittent wetland/lakes. http://www.worldwildlife.org/pages/global-lakes-and-wetlands-database	2004	<500 m buffer
Project opportunity area attributes	Rivers	Natural Earth	Natural Earth is a public domain map dataset featuring both cultural and physical vector data themes. The rivers datasets are originally from the World Data Bank 2. http://www.naturalearthdata.com/downloads/	Unknown (version 3.0.0)	
Project opportunity area attributes	Population density	LandScan (ORNL)	Oak Ridge National Laboratory's LandScanTM is the community standard for global population distribution. At approximately 1 km resolution (30" X 30"), it is one of the finest resolution global population distribution data available and represents an ambient population (average over 24 hours).	2012	
Resource assessment	Wind	Vaisala (formerly 3Tier)	Data were created from computer simulations using a meso-scale numerical weather prediction model and validated using publicly available wind speed observations. Annual average wind speed, wind power density, and wind power output were provided at 80 m hub height and 3.6 km resolution for a typical meteorological year.	10-year model run	<5.5 m/sec
Resource assessment	Solar DNI	NREL	Annual average direct normal irradiance data with a resolution of 10 km were provided by the National Renewable Energy Laboratory.	2014	<4.9 kWh/m^2-day
Resource assessment	Solar GHI	NREL	Annual average global horizontal irradiance data with a resolution of 10 km were provided by the National Renewable Energy Laboratory.	2014	<4.9 kWh/m^2-day

Stage of analysis	**Category**	**Source**	**Description**	**Year**	**Default exclusion thresholds**
Resource assessment	Protected Areas	World Database of Protected Areas (WDPA)	The World Database on Protected Areas (WDPA) is a comprehensive global spatial dataset on marine and terrestrial protected areas available. The WDPA is a joint project of UNEP and IUCN, produced by UNEP-WCMC and the IUCN World Commission on Protected Areas working with governments and collaborating NGOs.	2014	<500 m buffer
Resource assessment	Protected Areas	Protected Planet	Open source database that includes most WDPA locations, but also includes polygon representations of the WDPA point locations (those with unknown extents/boundaries)	2014	<500 m buffer
Project opportunity area attributes	Roads	gROADSv1 -Columbia University	Global Roads Open Access Data Set, Version 1 was developed under the auspices of the CODATA Global Roads Data Development Task Group at Columbia University. The dataset combines the best available roads data by country into a global roads coverage, using the UN Spatial Data Infrastructure Transport (UNSDI-T) version 2 as a common data model.	Variable; compiled 2010 (1980-2010)	
Project opportunity area attributes	Transmission substations	POSOCO	Transmission substation location data was provided by the Power Systems Operation Corporation of India, and various internet sources.	2016	

B. Supplementary Information: Estimates of electricity generation potential and levelized cost of electricity for concentrated solar power, solar PV and wind

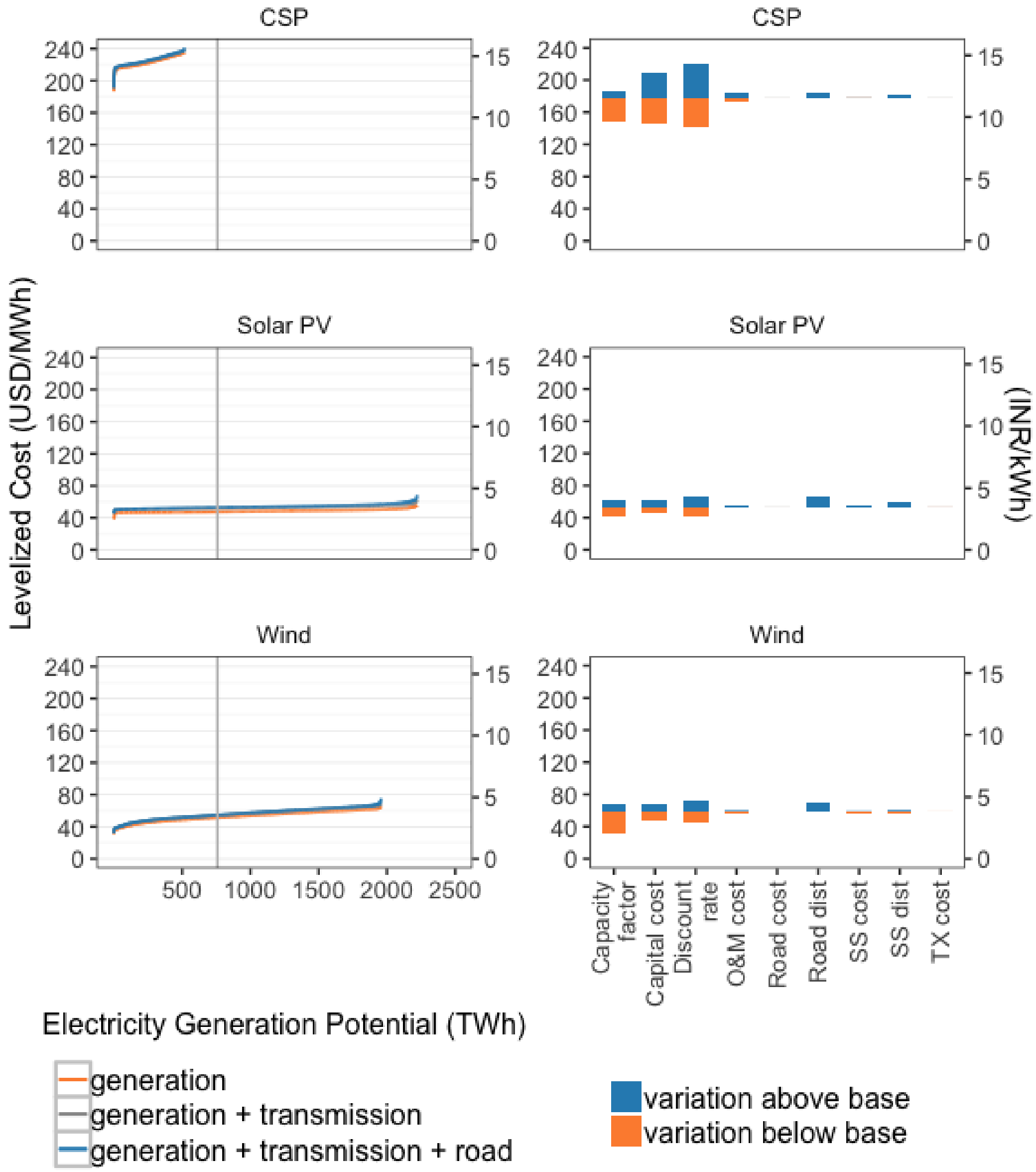

Figure B.10: (a) Electricity generation potential and levelized cost of electricity estimates for generation, transmission, and road for concentrated solar power (CSP), solar PV, and wind, and (b) total levelized cost of electricity sensitivity to multiple parameters. For sensitivity analysis, maximum, median (base), and minimum values for capacity factors and distances to nearest substation and road are estimates from this analysis; capital cost ranges are derived from lowest and highest 2017-18 auction prices for solar PV and wind, and from IRENA [3] for CSP; discount rate is varied from 4% to 10%; other parameters varied by +/- 20% of base values (Table 3). SS-substation. TX-Transmission.

C. Supplementary Information: Relationship between direct normal irradiance and concentrated solar power capacity factors

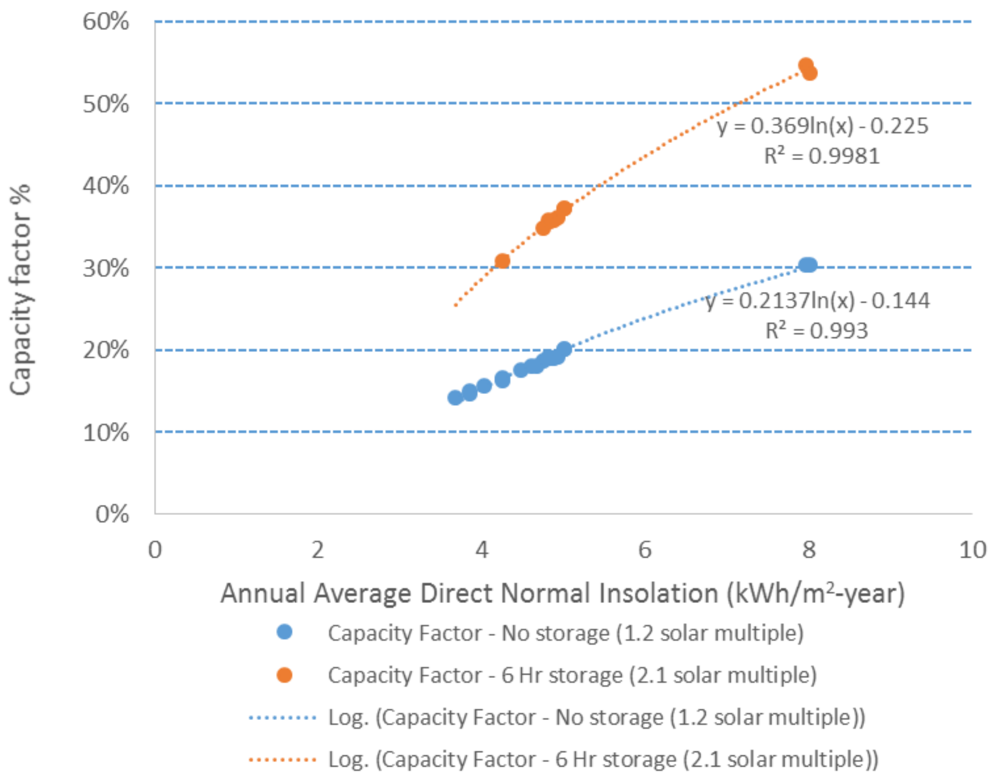

Figure C.11: **Relationship between capacity factor and Direct Normal Irradiance (DNI).** Capacity factors were simulated using the generic CSP plant in NRELs System Advisor Model for 19 locations across high quality resource areas in India. Logarithmic equations were fit to the simulated capacity factor data to statistically model the relationship between capacity factor and annual average DNI.

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